Thin Film Diluted Magnetic Semiconductors with Tetradymite Structure

Ctirad Uher   University of Michigan   DMR-0305221

- Ferromagnetic order in a semiconducting matrix offers exciting prospects for technological applications. Such diluted magnetic semiconductors (DMS) would have the capability to combine information characteristics (charge transport) with the information storage potential of magnetic media (spin manipulation). Worldwide focus is on the cubic, tetrahedrally bonded III-V semiconductors doped with Mn. We have recently discovered* ferromagnetism in an entirely different semiconducting matrix—the bulk tetradymite-type layered $A_2^{V}B_3^{VI}$ structure doped with vanadium or chromium. Such structures display octahedral coordination of atoms, Fig.1
- The aim of this work is to enhance the Curie temperature of DMSs based on Sb_2Te_3 and Bi_2Te_3 by increasing the amount of 3d transition metal dopants that can be incorporated into the structure. This will be achieved by growing thin films via a non-equilibrium MBE growth process. We will explore the influence of different 3d dopants and identify those that are most effective in stimulating magnetic order. Moreover, we aim to characterize the ferromagnetic state in this highly anisotropic environment of the tetradymite-type $A_2^{V}B_3^{VI}$ semiconducting structure.
- We have optimized the growth parameters for Sb_2Te_3 films on (0001) sapphire, Fig.2. The challenges ahead include finding the solubility limits for 3d transition metals in $Sb_{2-x}TM_xTe_3$ and $Bi_{2-x}TM_xTe_3$ films, establishing phase boundaries for different 3d metals, and ascertaining the mechanism leading to ferromagnetism in layered semiconducting matrices.

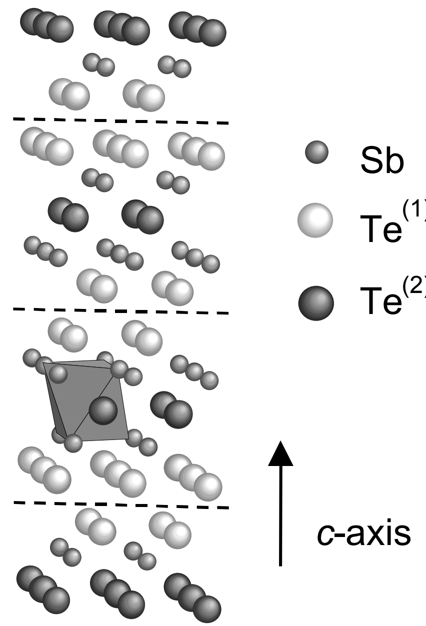

Fig.1:Atomic layers in the Sb_2Te_3 structure. Dashed lines indicate van der Waals gap. Octahedral coordination is highlighted.

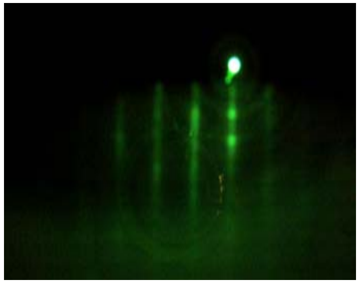

Fig.2: RHEED pattern of Sb_2Te_3 film grown on (0001) sapphire. Sharp streaks indicate high quality 2-d film growth.

Successful outcome would significantly broaden the range of DMSs and contribute to the understanding of physical processes that stimulate the long-range magnetic order in semiconducting structures.

* J.S. Dyck, P. Hajek, P. Lostak and C. Uher, Phys. Rev. B 65, 115212 (2002).

Motivation

The impetus for this project stems from our recent discovery of low temperature ferromagnetism in single crystals of the layered, narrow-band-gap semiconductor Sb_2Te_3 doped with very small concentrations of vanadium. The parent crystal, Sb_2Te_3, possesses the tetradymite structure characterized by octahedral bonding and a van der Waals gap separating five atom layer lamella, Te(1)-Sb-Te(2)-Sb-Te(1), in the plane perpendicular to the trigonal axis (Fig. 1). The bonding is primarily ionic and covalent within the layers (Te(1)-Sb and Sb-Te(2)), and the van der Waals force dominates between the Te double layers (Te(1)-Te(1)). Sb_2Te_3 is diamagnetic, just as the other pure tetradymite semiconductors, and little is known about the magnetic properties upon doping the structure. Crystals of both Bi_2Te_3 and Sb_2Te_3 grown under stoichiometric conditions have a high concentration of holes due to antistructural defects (Sb or Bi atom in a Te position).

In this project, we extend the study of the tetradymite-type diluted magnetic semiconductors to material in thin film form. The research involves the first study of doping tetradymite structures with transition metal impurities through the use of MBE growth. It is expected to establish the phase boundary between the paramagnetic and ferromagnetic states in these compounds by exploring the influence of species and concentration of 3d magnetic ions. Another important aspect of this research is detailed characterization of the nature of the ferromagnetic state in these materials and the roles played by the composition of the host matrix as well as magnetic impurities.

Significance of results

Diluted magnetic semiconductors attract worldwide attention because they combine intrinsic scientific interest (how does the magnetic order develop in a low-carrier density medium) with a great potential for technological applications via its dual feature of charge carrier transport and spin manipulation. Unlike the traditional DMSs based on Mn-doped III-V and II-VI compounds, our effort focuses on the magnetic interactions in a highly anisotropic environment of the tetradymite-type crystal lattice stimulated by the presence of a variety of 3d transition metals and not just Mn. Our work thus significantly extends the domain of DMSs and the results should have an important impact on the understanding of magnetism in low carrier density systems. Tetradymite-type semiconductors such as Bi_2Te_3 and Sb_2Te_3 are the archetypal thermoelectric materials forming the base of all thermoelectric cooling devices. Combining this attribute with their spintronics potential would open exciting possibilities for designing a variety of thin film detectors and sensors.

Future plans

In the near future, the emphasis will be on establishing solid solubility limits for vanadium and chromium in thin films of Sb_2Te_3. This is a crucial step in order to enhance the Curie temperature. Further tuning of the magnetic properties will be done by controlling the carrier density via doping. We are also eager to explore the influence of film thickness on the magnetic characteristics of the structure as the shape effect will play an increasing role as one makes the films thinner. This should influence the coercive field and perhaps even the orientation of spins.

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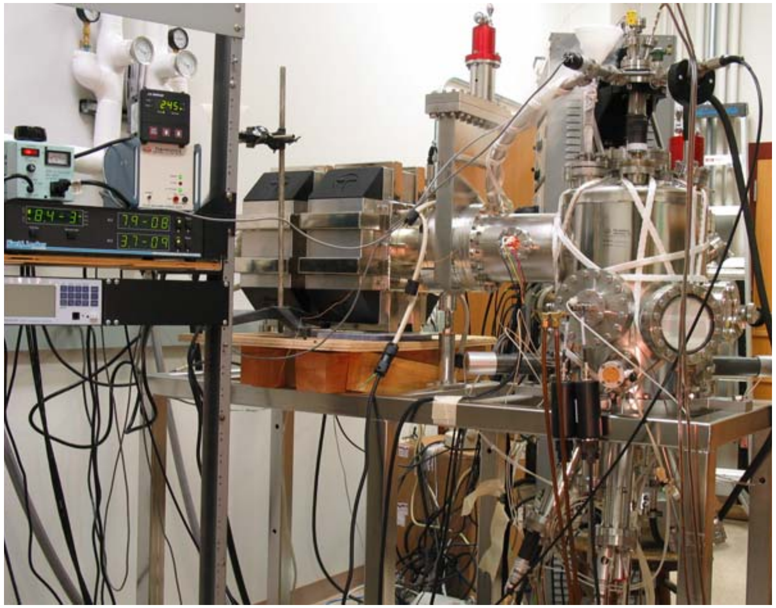
Facilities:

The growth of films is done using a dedicated MBE system equipped with three K-cells and a miniature E-gun. The structural quality of the growing films is monitored using a RHEED system. Magnetic and transport properties of the films are measured in a SQUID-based Magnetic Property Measuring System in fields up to 5T.



Education:

This work is a thesis project of Y.J. Chien, a second year student enrolled in our Applied Physics graduate program. In addition, in the early stages of the project my then postdoc, Dr. Jeffrey Dyck, participated in the design and testing of our new MBE chamber and associated hardware. Dr. Dyck is now an Assistant Professor at the Physics Department of John Carroll's University in Cleveland. During the summer, I supported and much enjoyed the presence of a talented second year undergraduate student, Peter Landry.

Outreach:

As Chair of the Department during the past 10 years, I organized and supported a series of public lectures called Saturday Morning Physics. These lectures are given by our postdocs (Fall term) and faculty (Winter term) and attract wide and diverse audience (attendance in excess of 250 each Saturday morning football season or not from middle school kids to senior citizens). The lectures highlight research work conducted in our department and my group is an active participant.